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The efficacy of good practice to prevent long-term leaching losses of phosphorus from an irrigated dairy farm

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ABSTRACT

Phosphorus (P) can be leached from intensive land uses, including grazed dairy farming. There is some evidence to suggest that P-leaching can enrich groundwater, especially where fertiliser or farm dairy effluent P (FDE) is applied to soils of low sorption capacity. We measured P fractions in leachate at 70 cm depth from two soils of low-P sorption capacity in an intensively grazed dairy farm, one a free-draining shallow soil and another a deep and moderately well-drained soil. As per industry good practice, the soils were maintained at an agronomic optimum and received P as either fertiliser or a lower rate of fertiliser plus FDE, applied according to regional rules and industry guidelines to avoid the FDE ponding on the soil surface and leaching to depth. Our hypothesis was that rules and guidelines were not sufficient to prevent P losses, especially in the free-draining soil. In response to annual applications of 40 kg P ha^{-1} yr^{-1} as fertiliser or 30 kg P ha^{-1} yr^{-1} as fertiliser and 10 kg P ha^{-1} yr^{-1} as FDE, dissolved and particulate P concentrations increased annually 4 to 7%. Mean total P load over the 14-yr period of measurement (2001–2015) from the FDE-treated, free-draining shallow soil was 1.46 kg ha^{-1} yr^{-1}, much greater than the same soil without FDE (0.25 kg ha^{-1} yr^{-1}) or the moderately well-drained soil with or without FDE applied (0.12 kg ha^{-1} yr^{-1}, for both treatments). Leaching losses were attributed to a combination of high hydraulic conductivity enhanced by the presence of macropores and the increasing P saturation of macropore walls. An enrichment in dissolved reactive P was also detected in a well intercepting groundwater at 10-m depth. However, the source of the enrichment was unclear. These data suggest that despite following industry good practice, regional rules and industry guidelines significant P losses may occur when FDE is applied to soil at rates designed to maintain soil Olsen P in an agronomically optimal concentration. It is unclear if applying less FDE at lower rate, would decrease P losses. Therefore, less P must be applied, made less available for loss, or P-rich FDE not applied to this freely draining shallow stony soil (or similar soils) under irrigation.

1. Introduction

The diffuse loss of phosphorus (P) from land is widely recognised as a key factor in the eutrophication of surface waters (Carpenter, 2008). Losses from grazed grassland systems are thought to occur largely as surface runoff proportional to: 1) the distribution, amount and rate of rainfall (Ockenden et al., 2016); 2) soil conditions that promote surface runoff (Owens et al., 2012); 3) soil test P concentrations (Lewis et al., 2013); 4) the application of P-rich manure or dung from grazing animals onto topsoil (Gourley et al., 2015); and 5) the degree of animal treading that enhances the likelihood of soil erosion (Cournane et al., 2011). However, substantial P loss may also occur via subsurface pathways. For instance, substantial P losses have been reported where subsurface transport has been facilitated by preferential flow that bypasses the soil matrix using macropores, especially if macropores are connected to an artificial drainage network (Monaghan et al., 2016). Similarly, P-leaching to deeper soils layers (e.g. 1-m below the topsoil) has been noted in sandy or organic soils with poor P sorption capacity, especially where large amounts of manure have been applied (Koopmans et al., 2007; Pizzeghello et al., 2016). Some work has also shown that P can move laterally via preferential flow paths to nearby streams (Fuchs et al., 2009), or deeper into groundwater (Holman et al., 2010). These studies have focused on high-risk factors that singularly enhance P-leaching losses. However, they have not addressed the possibility that factors individually considered of moderate risk could combine, especially over the long-term, to cause large P-leaching losses,

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or that regulation or guidelines to reduce P losses could be ineffective.

Studies of P-leaching from long-term trial sites are rare, typically examining periods of no more than 3 years (Haygarth and Jarvis, 1997; Oliver et al., 2005). However, with a continuous record, long-term sites enable temporal trends to be established that reveal risks associated with incremental or slow changes in soil conditions. For example, at the Broadbalk continuous wheat experiment at Rothamsted (Harpenden, UK), > 150 years of farm yard manure applications was thought to have saturated the P-sorption sites of soil macropores leading to enhanced P losses in drainage water (Jensen et al., 1998). In grazed dairy systems, manure is not applied, instead wash down water from the milking parlour is collected in ponds. The resulting farm dairy effluent (FDE) has few solids (< 1%), but is rich in particulate-P, organic compounds and unreactive P that could be easily transported through macropores (Monaghan et al., 2010). Sustained application could affect the P sorption capacity of macropore walls, as seen in the Broadbalk example. Short-term studies of manure applied to soil suggest that particulate P (of which colloidal P is a significant component) and unreactive P (i.e. organic P) may be more leachable than orthophosphate (Ekholm and Krogerus, 2003; Uusitalo et al., 2003; Leytem et al., 2004). Toor et al. (2005) found that the application of 40–80 kg P ha^{-1} yr^{-1} of FDE enhanced the loss of particulate unreactive P over orthophosphate, but this study only occurred for 18 months. Few data exist to determine if long term FDE applications enhance the risk of losing a greater quantity and diversity of P fractions than soils receiving P as inorganic fertiliser.

The New Zealand dairy industry accounts for 65, 55, 16 and 16% of whole milk powder, butter, skim milk powder and cheese exports amongst the top ten exporting countries, globally (European Commission, 2018). The Canterbury region is the second largest dairy producing region in New Zealand (DairyNZ, 2016). The region relies on irrigation to maintain pasture growth in soils with a moderate to low water holding capacity, commonly 30-120-mm (Carrick et al., 2013). These soils also have a low to moderate anion storage capacity (ASC = 20–40%), which correlates to P sorption capacity (McDowell and Condron, 2004). Although these factors are recognised to be of moderate risk for P-leaching under intensive land use (Webb et al., 2010), a number of guidelines and regulations are in place to minimise P losses from this nationally and globally important dairy region. These stipulate that FDE is applied according to: 1) regional authority rules to avoid the ponding of FDE on the soil surface (Canterbury Regional Council, 2015); 2) an industry Code of Practice that calls for no more than 10-mm of FDE to be applied at one time and not within 24-hrs of saturation for a shallow soil with < 50% profile available water in the upper 30-cm of topsoil thereby avoiding application in winter months (DairyNZ, 2015); and 3) 'good practice' guidelines for soil test P concentrations, which keep them at or below the agronomic optimum by adjusting P applications to meet pasture P-demand (Roberts and Morton, 2009). These fertiliser and irrigation regulations and recommendations are similar to those for irrigated land, globally (USDA-Natural Resources Conservation Service, 2012; The Fertilizer Institute, 2018), but may not be sufficient to minimise P concentrations or loads to an acceptable level.

The Lincoln University Dairy Farm (LUDF) was established in 2001 and is used as a regional demonstration farm showing how high quantities of milk solids can be produced while minimising its environmental footprint (Lincoln University, 2017). The analysis of P fractions in leachate from an extensive array of lysimeters and groundwater means that there is now a long-term record from which we can: 1) determine the magnitude and any patterns (e.g. trends) of P leaching losses from two different soils representative of those used for dairying in the wider Canterbury region for intensive irrigated dairying; 2) determine if there was a difference in P losses caused by the application of FDE to two these soils despite following rules, guidelines and good practice; 3) determine if P is being lost to groundwater; and 4) recommend additional actions to mitigate P losses.

2. Materials and methods

2.1. Site details and treatments

The LUDF is 15 km South West of Christchurch, New Zealand and has mean annual maximum and minimum temperatures of 17 and 4 °C, respectively, and a mean annual rainfall of 650 mm. The farm has an effective area of 160 ha and in recent years an average stocking density of 3.5 cows ha^{-1}. Approximately 500 mm ha^{-1} yr^{-1} of irrigation water is sprayed onto 127 ha via centre-pivot irrigators, with the remainder of the farm irrigated by hand-shifted sprinklers and 10 ha of 'K-line' sprinklers (RX Plastics, Ashburton, New Zealand). The irrigation season normally runs from September to March, though is dependent on rainfall and soil moisture levels. At its fastest rate the centre pivot irrigated area can deliver 5.5 mm daily, but is adjusted according to forecast rainfall and the daily soil moisture measured in the top 50 cm using 'Aquaflex' soil moisture sensors (STREAT Instruments, Christchurch, New Zealand) dug into each of the farm's soil types. Pastures are primarily perennial ryegrass (*Lolium perenne)* and white clover (*Trifolium repens*). Livestock are Holstein–Friesian based with a mature live weight of nearly 500 kg cow^{-1} and produce 500–520 kg of milk solids (MS) cow^{-1} or 1750 kg MS ha^{-1} yr^{-1}. Cows graze the farm year round, except during the winter, non-lactating period (June - July), when up to 100% of the herd may be off-farm due to low winter pasture growth rates. Cows graze paddocks rotationally on a 24-day grazing round for most of the year, with longer grazing rotations in early spring and autumn. On average, the cows graze each paddock for 24 h before moving to a new paddock, grazing down to a residual of c. 1600 kg dry matter (DM) ha^{-1}.

The farm contained five soil types (Fig. 1). Two of them, a shallow stony Eyre silt loam and deep Templeton silt loam, were used in this study and are representative of the soils used for irrigated dairy farming in the Canterbury region (Webb et al., 2010; Carrick et al., 2013). These two soils are classified using the New Zealand Soil Classification as Typic Orthic Recent and Typic Immature Pallic soils, respectively, or as Typic Dystrustept and Typic Haplustept, respectively, in US Soil Taxonomy (Webb et al., 2000).

Fertiliser applications are based on individual paddock soil testing and designed to meet pasture demand as determined by the nutrient budgeting software - Overseer (AgResearch, 2016) for most macro-nutrients (particularly P and potassium). Approximately 170 kg nitrogen (N) ha^{-1} yr^{-1} fertiliser is applied annually. Nitrogen is applied following each grazing event at 25 kg N ha^{-1}, while P (applied as single superphosphate) is normally applied in one application in October (spring). The FDE area is excluded from N-fertiliser applications, except following the first spring grazing. The remaining 145 kg N ha^{-1} yr^{-1} is applied as FDE. The average P application rate across the farm from 2010 to 2015 was 40 kg P ha^{-1} yr^{-1}, with the FDE area receiving 30 kg P ha^{-1} yr^{-1} as superphosphate and 10 kg P ha^{-1} yr^{-1} as FDE.

Farm dairy effluent from washing down the dairy shed is collected during the milking season and flows through a concrete 'stone trap' tank, removing heavy or large solids, into a larger 33,000 l sump tank containing an effluent pump and stirrer. Farm dairy effluent is transferred to a 300,000 l capacity 'enviro-saucer' storage pond prior to application to the land. This system provides storage to avoid having to apply FDE onto wet soils. The FDE is applied to land every 1–2 days through a pipe and sprinkler system attached beneath the centre pivot irrigation system. The FDE does not mix with the water in the irrigation pipe system. The FDE adds about 40–50 mm of liquid to the soil annually.

2.2. Lysimeters and wells

Sixty lysimeters (50 cm diameter and 70 cm deep) with edge-flow protection (Cameron et al., 1992) were installed in 2001. Lysimeters were located in four arrays: thirty on the Eyre soil and thirty on the

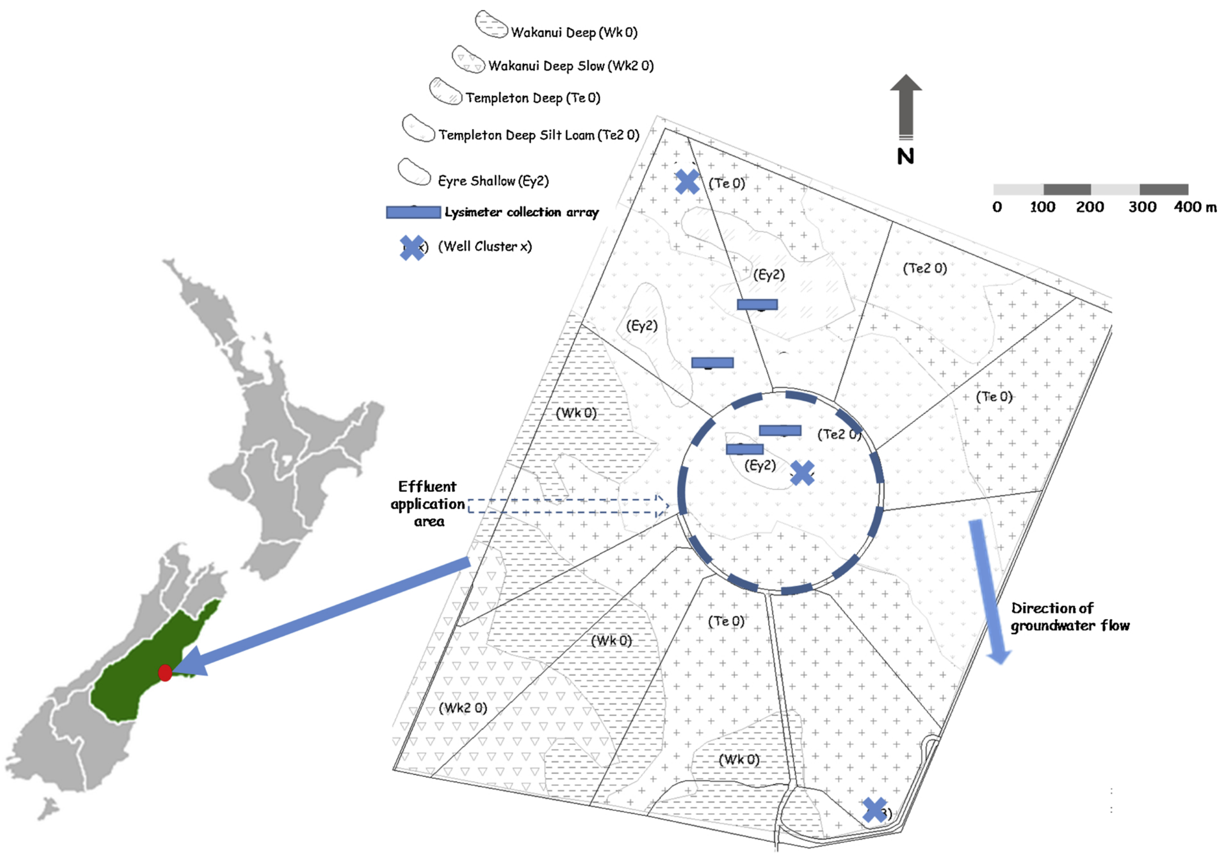

Fig. 1. Map showing the arrangement of lysimeter arrays and clusters of groundwater inception wells relative to soil types, farm dairy effluent application areas, and the direction of flow.

Templeton soil. Twenty lysimeters of each soil type were located in the FDE-treated area and 10 of each soil type outside the FDE area (Fig. 1). Lysimeters were spaced 1-m apart and housed within a bunker that allowed for access to the bottom of the lysimeters to collect leachate. Apart from the access points, lysimeters were grazed the same as the rest of the paddock. Leachate samples (n = 8086) were collected in response to 305 rainfall events from January 2001 to December 2015. Leachate volumes per event varied from 0.1 to 37 l per lysimeter. All samples were filtered (0.45 μm) at the time of collection and stored frozen along with an unfiltered sample until analysed. Sub-sampling of leachate samples for this analysis began in 2001 and finished at the end of 2015.

Prior to operating the farm as an irrigated dairy farm, seven wells were drilled to 10-m to intercept and allow for the sampling of groundwater at three clustered locations: three of these wells were up-gradient of the farm, two in the middle and two down-gradient of the farm (Fig. 1). Spacing between well in each cluster was up to 50-m apart. Sampling began from one well at each site in March 2001, but owing to inadequate resourcing, all the other wells were sampled from October 2005. Groundwater samples were taken once every season, filtered (< 0.45 μm) on-site and stored frozen until analysed (n = 363 for all wells, but 65 and 57 for the two long-term up- and down-gradient wells used to determine trends in DRP). Sub-sampling of groundwater samples for this analysis finished at the end of 2015.

2.3. Analyses

Twelve soil samples were taken of the 0–7.5 cm, 7.5–15, 15–30, and 30–60 cm soil depths in May 2015 within a 20 m radius of each lysimeter array. Taking samples to 7.5 cm and 15 cm depths are standard in New Zealand for agronomic testing of pasture and crop growth, respectively (Nicholls et al., 2009; Roberts and Morton, 2009). Soils were air-dried, crushed, sieved < 2 mm and analysed for ASC which measures the quantity of P-sorbed from a 1 g L^{-1} solution on a scale from 0 to 100% (Saunders, 1965), and has been shown to directly relate to the potential for P-leaching (McDowell and Condron, 2004). Soils were also measured for pH (1:2 soil to water ratio) (Hendershot et al., 1993), organic carbon (LECO C/N analyser), sand and clay (Beuselinck et al., 1998), cation exchange capacity (CEC) (Sumner and Miller, 1996), Olsen P (Olsen et al., 1954), and water extractable P (WEP). Water extractable P is designed to estimate P concentrations in runoff (McDowell and Condron, 2004).

Leachate samples were analysed for dissolved reactive P (DRP, but also called filterable reactive P by some), while total dissolved P (TDP, but also called total filtered P by some) and total P (TP), were determined on filtered and unfiltered samples that had been digested using acidified persulphate (Eisenreich et al., 1975). Dissolved unreactive (*viz.* organic) P (DURP) and particulate P (PP) were defined as the difference of TDP and DRP and TP and TDP, respectively. All P analysis was undertaken on a Seal AA3 discrete auto analyzer (Seal Analytical Inc. Mequon WI) using standard USEPA Method 365.1 (O'Dell, 1993). The detection limit (DL) for DRP was 1 μg L^{-1} and 2 μg L^{-1} for TDP and TP, resulting in a DL for DURP and PP of 1 μg L^{-1}. The proportion of samples < Dl for leachate samples was < 2%, but averaged 5% for groundwater samples. Where < DL, samples were set at half the DL. Load calculations for each event (the product of drainage volume and P concentration) were summed across events for each lysimeter to give a total annual load.

2.4. Statistical analyses

Soil data were checked for normality and analysed via a two-way analysis of variance (ANOVA) setting treatment (soil type with or without FDE) and depth as factors. Corresponding P values are presented to contrast for each factor and their interaction, and augmented by the least significant difference at the $P < 0.05$ level (LSD_{05}) to contrast means across treatments and depths.

Data for the concentrations of P fractions and loads amongst treatments were log-transformed to correct for skewness. Data for concentrations were analysed by a one-way ANOVA to contrast the mean concentrations of P fractions using season as a factor for each soil type by FDE treatment combination. A two-way ANOVA was used to contrast mean annual loads of P fractions setting soil type and FDE as factors. Significant differences are presented for P fractions at the $P < 0.05$ level of significance, while the corresponding P values are presented to contrast loads by soil, FDE and their interaction, and augmented by a LSD_{05} to contrast individual soil by FDE mean annual loads. Both one- and two-way ANOVAs were conducted using GENSTAT for Windows v13.2 (Genstat Committee, 2015).

Trends in the concentrations of P fractions in leachate and groundwater over time were tested using a seasonal Kendall test to correct for potential seasonality. The Sen Slope Estimator (SSE) was used to represent the magnitude and direction of trends in median concentrations. Trend analysis was conducted using Time Trends software v3.31 (Jowett, 2009).

3. Results and discussion

3.1. Soils

Data for soil chemical and physical properties are shown in Table 1. Data were examined to determine if mean properties differed between the treatments (soil type and FDE combinations), and by depth for any treatment. Amongst treatments, ASC was enriched in the Eyre soil receiving FDE. Phosphorus sorption capacity, which is related to ASC, has been shown to increase (Abdala et al., 2015), decrease (Guppy et al., 2005) or have no effect (Afif et al., 1995) depending on the amount, fraction and composition of dissolved and particulate organic matter introduced to the soil. While organic matter in FDE could increase ASC in the Eyre soil, no significant changes in organic carbon were noted (Table 1). It is therefore more likely that ASC enrichment was caused by analytical variability or natural variation arising from gravels lenses associated with old river beds in the region (Carrick et al., 2013).

Concentrations of Olsen P, WEP, organic C, CEC and clay all decreased with depth, while the proportion of sand increased (Table 1). The decreases in organic C, Olsen P and WEP likely reflect the greater plant root biomass in the topsoil while the stratification of Olsen P and WEP were likely caused by the surface application of P fertiliser to pastures (Sharpley, 2003). Increases in the percentage of sand (and decrease in percentage clay) with depth reflect the transition to a stony B horizon in the Eyre soil, which extends to aquifer gravels at 1–2-m depth (Webb et al., 2010; Carrick et al., 2013).

Amongst treatments, Olsen P and WEP concentrations were enriched in the 0–7.5 7.5–15 and 30-60-cm layers of the Eyre + FDE treated soils compared to the untreated Eyre soil (Table 1). This enrichment did not occur in the Templeton soil treated with FDE. Slower infiltration rates may have allowed for more sorption by the soil, while greater mean organic C concentrations may have allowed for P to be stored as organic P (Hou et al., 2014). Many studies have shown that P can leach and enrich soil P to depth (Chardon and Schoumans, 2007; Holman et al., 2008; Bergström et al., 2015). Enrichment at depth has been attributed to a number of factors such as: the application of P in-excess of plant requirements (Kleinman et al., 2015); extremely low ASC < 10% (i.e. P sorption capacity) (McDowell and Monaghan, 2015); the inhibition of P-sorption sites by organic compounds in manure (Liu et al., 2015); and soil physical conditions such as a coarse texture or the presence of macropores that enhance the transport of leachate to depth (Schoumans and Groenendijk, 2000). Examining each of these factors independently suggests that different soil physical characteristics were the most likely cause. For example, the Eyre soil

Table 1
Mean soil chemical and physical characteristics at different depths for the Eyre and Templeton soils with or without farm dairy effluent (FDE) application in 2015. Corresponding P values are given to contrast the significance of treatments (the application of FDE) and depth along with the least significant different at the $P < 0.05$ level to enable comparison of means for specific treatment by depth combinations.

Treatment / Depth	Anion storage capacity (%)	pH	Organic carbon (g kg^{-1})	Cation exchange capacity (cmol kg^{-1})	Sand (g kg^{-1})	Clay (g kg^{-1})	Olsen P (mg L^{-1})	Water soluble P (μg L^{-1})
Eyre								
0-7.5	20	6.1	27.5	15	210	160	31	93
7.5-15	22	6.2	17.5	10	240	175	19	72
15-30	21	6.1	9.4	10	210	195	9	78
30-60	20	6.1	7.2	9	310	110	9	75
Overall	21	6.1	15.4	11	242	160	17	80
Eyre + FDE								
0-7.5	23	6.4	35.2	16	215	220	43	164
7.5-15	25	6.2	28.6	14	230	240	27	126
15-30	26	5.9	22.1	14	205	225	16	103
30-60	25	5.8	16.9	11	340	90	16	108
Overall	25	6.0	25.7	14	248	194	26	125
Templeton								
0-7.5	14	7	37.1	16	455	240	31	148
7.5-15	17	7	27.6	14	360	275	26	104
15-30	18	6.9	15.3	11	330	225	11	96
30-60	11	7	2.7	8	405	215	9	54
Overall	15	7	20.6	12	388	239	19	100
Templeton + FDE								
0-7.5	18	6.6	37.9	16	405	225	35	133
7.5-15	21	6.4	29.7	14	355	260	25	92
15-30	20	6.4	18.9	13	335	220	15	121
30-60	17	6.3	6.4	9	370	210	14	82
Overall	19	6.4	23.2	13	367	229	22	107
P-values								
Treatment (FDE)	< 0.05	ns	ns	ns	ns	ns	ns	ns
Depth	ns	ns	< 0.01	< 0.01	ns	< 0.05	< 0.001	< 0.001
Treatment × depth	< 0.01	< 0.05	< 0.01	< 0.001	< 0.05	< 0.05	< 0.001	< 0.001
$LSD_{treatment \times depth}$	5	0.5	14.2	4	95	75	6	31

received the same rate of P as either FDE + fertiliser or as fertiliser, designed to place the soil within the optimum range for agronomic production (Morton et al., 2003; Roberts and Morton, 2009). This strategy resulted in similar Olsen P concentrations across the treatments. The ASC of the Eyre soil is classified by Hewitt (1998) as low, but ASC was similar to the Templeton soil (Table 1). However, the Eyre soil is stonier and shallower than the Templeton soil and hence freer draining. Webb et al. (2000) showed that in the A Horizon, macroporosity and hydraulic conductivity were greater in the Eyre than Templeton soil (macroporosity = 11.4 v 9.1%, respectively; hydraulic conductivity = 340 v 91 mm hr^{-1}), but much greater in the B-horizon (> 30-cm deep) for the Eyre soil (macroporosity = 10.5 v 5.6%, respectively; hydraulic conductivity = 24 v 2.7 mm hr^{-1}). Several studies have shown P leaching occurs on coarse textured or stony soils, either through fast matrix flow or through macropores (Ozanne et al., 1961; Koopmans et al., 2007). With FDE being applied as a dilute liquid (< 1% solids) this suggests that even for a modest P application rate, P movement to depth would be facilitated by the porous structure and free draining nature of the Eyre soil.

3.2. Leachate

Mean drainage volumes were greater ($P < 0.05$) from the Eyre than Templeton soils, especially in the Eyre soil receiving FDE (Table 2). This was supported by an average increase in annual volumes of drainage from the Eyre soil treated with FDE (Seasonal Kendall test; $P < 0.05$) by 7.5%. Drainage most likely reflected the greater porosity and hydraulic conductivity of the Eyre soil, but may have also been enhanced by the 40–50 mm of liquid applied as FDE over and above the application of irrigation water. Previous studies have shown that the regular application of FDE can increase soil structural stability (Barkle et al., 2000; Roach et al., 2001), in turn improving macroporosity and drainage via macropore flow (Tisdall and Oades, 1982; Haynes and Naidu, 1998). Other studies, using a Lismore silt loam (analogous to the Eyre silt loam soil) and the Templeton soil, confirmed the presence of macropores as the rapid leaching of solutes through soil cores or lysimeters compared to a much slower leaching loss when macropores were not allowed to conducted flow under 0.5 kPa suction (Silva et al., 2000; Toor et al., 2005).

Annual loads for P fractions lost in leachate varied from a low of 0.03 kg DURP ha^{-1} from the Templeton soil to 1.46 kg TP ha^{-1} from the Eyre + FDE treatment (Table 2). The magnitude of TP lost in leachate from all but the Eyre + FDE treatment was similar to that of a 21 month study by Toor et al. (2005) who measured leachate losses to 70 cm of 0.3 kg TP ha^{-1} yr^{-1} from a closely related Lismore stony silt loam (Typic Dystrustept) receiving 45 kg P ha^{-1} yr^{-1} as superphosphate. When Toor et al. (2005) augmented the 45 kg P ha^{-1} yr^{-1} applied as superphosphate with 40–80 kg P ha^{-1} yr^{-1} sprayed onto the soil surface as FDE, losses increased to 1.6–2.3 kg P ha^{-1} yr^{-1} – similar to the long-term average measured in the Eyre + FDE treatment. More importantly, in the Templeton soil, the load of P lost was similar across all fractions, whereas in the Eyre soil PP was the dominant fraction. As PP is normally filtered-out during matrix flow (Heathwaite and Dils, 2000), the enrichment of PP in the Eyre soil points to preferential flow through macropores. This is especially true for FDE-treated soil whose PP enrichment (56% of TP) is indicative of the high proportion of TP as P-rich particles (> 60% of TP) within FDE (Houlbrooke et al., 2008), and enrichment in summer (Fig. 2) when the soil is most likely to exhibit periods of desiccation and cracking. Although an equivalent amount of P was applied as fertiliser, applications were timed as per good practice when rainfall was not forecast. This practice maximises the chance that fertiliser-P would sorb into the soil and not be washed into macropores.

Table 2
Mean annual drainage and the loads (kg P ha^{-1} yr^{-1}) of P fractions lost in leachate from the Eyre and Templeton soils with or without farm dairy effluent (FDE) application. (DRP = dissolved reactive P; DURP = dissolved unreactive P, PP = particulate P, TP = total P). The least significant difference (LSD) for the interaction of soil type × FDE application is given at the $P < 0.05$ level of significance.

Treatment	Drainage (mm)	DRP	DURP	PP	TP
Eyre (n = 10)	285	0.071	0.061	0.113	0.245
Eyre + FDE (n = 20)	319	0.316	0.329	0.816	1.461
Templeton (n = 10)	231	0.048	0.030	0.039	0.117
Templeton + FDE (n = 20)	204	0.050	0.031	0.042	0.122
P-values					
Soil	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
FDE	< 0.05	< 0.001	< 0.001	< 0.001	< 0.001
Soil × FDE	< 0.05	< 0.001	< 0.001	< 0.001	< 0.001
$LSD_{05\ soil\ \times\ FDE}$	62	0.059	0.054	0.145	0.245

With repeated applications it is possible that the leaching of FDE through macropores has decreased the P-sorption capacity of macropore walls (Djodjic et al., 1999; Simard et al., 2000; Mittelstet et al., 2011). A trend analysis indicated that median concentrations for many of the P fractions had increased over the 14-year period of record, although the Eyre + FDE treatment was the only treatment to show enrichment across all P fractions (Table 3). AS an example of enrichment, the relative magnitude of DRP concentrations across soil types by FDE treatments is shown in Fig. 3. Differences between the FDE and non-FDE treated Eyre soils were most apparent during the irrigation season (November to March) when FDE was also being applied. Using log-transformed data, the mean DRP concentration for the period of 2002–2005 was 117 μg L^{-1} in the Eyre + FDE treatment was significantly less ($P < 0.05$) than the mean DRP concentration for 2012–2015 at 289 μg L^{-1}.

Interestingly, an enrichment in DURP concentration was noted for all treatments. This supports an hypothesis that DURP is able to travel through the fine-textured and stony soils owing to the poor sorption of some organic P compounds (Toor et al., 2005; Wang et al., 2013). However, it should also be noted that studies have also shown that many organic P species to be more strongly sorbed to soil than orthophosphate (Leytem et al., 2002; Berg and Joern, 2006).

3.3. Groundwater

Mean groundwater P fraction concentrations (Table 4) for bores up-gradient, at the mid-point in the farm, and down-gradient of the farm were less than those measured in the leachate from any treatment ($P < 0.05$), presumably a reflection of decreasing macroporosity and preferential flow with depth forcing P-rich leachate to flow through the subsoil by matrix flow and be sorbed (Webb et al., 2000). Over the period of record, concentrations were similar between sites. However, these data contained a mixture of records, with only one bore at the up-gradient and down-gradient site having samples for the same 14-year period as the lysimeters. Restricting the analysis to these long-term bores indicated that the mean concentration of DRP at the long-term downstream well (4.2 μg L^{-1}) was greater ($P < 0.05$) than at the up-gradient well (1.6 μg L^{-1}), owing to an annual mean enrichment of DRP at the down-gradient well of 8.4%. However, this enrichment should be interpreted with caution, as it did not occur in the other P fractions and, furthermore, the majority of farm was covered by the lower P-leaching Templeton soil.

Leaching of P to groundwater has been noted where land use intensity is high (Holman et al., 2010), the soil is free-draining or poorly sorbs P (Mabilde et al., 2017), there is large legacy pool of soil P, or the soil receives high application rates of P (Toor and Sims, 2015). In a New Zealand context, McDowell et al. (2015) found a statistical relationship occurred between groundwater P-enrichment and the presence of irrigated and grazed dairy pastures on soils of a low ASC (< 20%) and

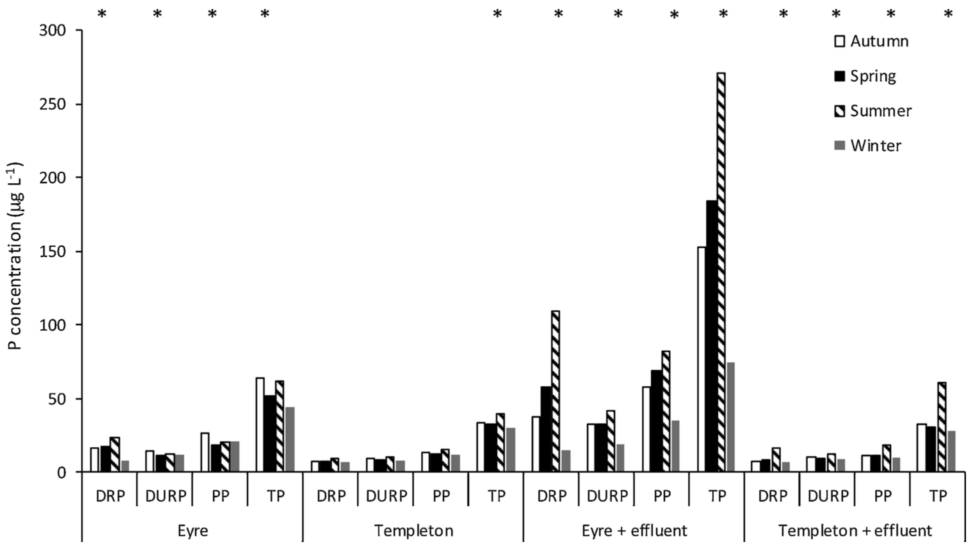

Fig. 2. Mean seasonal concentration of P fractions (DRP = dissolved reactive P; DURP = dissolved unreactive P, PP = particulate P, TP = total P) in leachate collected from each treatment between 2001 and 2015. An asterisk indicates a significant difference ($P < 0.05$) in the log-mean concentration of a P fraction between treatments within a season.

Table 3
Median concentrations of P fractions in leachate for Eyre and Templeton soils with or without farm dairy effluent (FDE) application. The Sens Slope Estimator (SSE) used to indicate a significant ($P < 0.05$) annual percentage change (> 1%) in the median concentration over the 14-year period of record.

Analyte / Site	Median concentration (µg L^{-1})	SSE (% annual change in median concentration)
DRP		
Eyre	19	–
Eyre + FDE	50	4.1
Templeton	7	−4.1
Templeton + FDE	10	–
DURP		
Eyre	13	4.9
Eyre + FDE	30	7.3
Templeton	9	4.3
Templeton + FDE	10	4.6
PP		
Eyre	21	6.2
Eyre + FDE	63	6.6
Templeton	13	–
Templeton + FDE	12	–
TP		
Eyre	57	4.5
Eyre + FDE	171	4.9
Templeton	32	–
Templeton + FDE	37	–

moderate to high soil Olsen P. Although the down-gradient well was overlain by a Templeton soil, aquifer gravels in the area have been shown to transmit FDE-sourced P hundreds of metres (Close and Woods, 1986; Gray et al., 2015). Therefore, the leaching of P into the aquifer from the FDE-treated Eyre soil, and detecting this P down-gradient of the farm is possible. However, this is just as likely to have come from surrounding high-intensity land uses (including arable, poultry farms). Therefore, we cannot say that the signal detected was exclusively from this farm's FDE practices.

3.4. Management implications

Current good practice for dairy farms in New Zealand and overseas is to only apply as much P as required to achieve an agronomic optimum yield (Gourley et al., 2015) and maintain this yield with fertiliser and FDE applied according to rules that prohibit the ponding of FDE on the soil surface especially in wet or winter months (Canterbury Regional Council, 2015; Liu et al., 2018). However, in the freely-drained, shallow Eyre soil, this did not prevent P losses. This is of concern, given shallow stony soils like the Eyre soil cover about 143,000 ha under dairying in Canterbury (Carrick et al., 2013).

The potential for P loss could be decreased by reducing P applications and soil Olsen P concentrations (Sharpley et al., 2013). However, as the soils were only occasionally above the agronomic optimum of 35 mg L^{-1} for top producing farms in a region (Roberts and Morton, 2009), this wouldn't decrease P losses much and may risk impairing pasture yield. However, the transport of available P could be minimised by only irrigating to meet the moisture needs of the plant, and avoiding drainage. Recent developments in the precision application of water now tailor the quantity of water to the spatial extent of a soil's available water holding capacity (Hedley et al., 2010). Varying the depth of irrigation on a daily basis can minimise the quantity of drainage, which can be minimised further by adjusting applications according to weather forecasts. Compared to uniform rate irrigation, the use of variable rate irrigation (or more precisely, depth at a static rate) has been shown to decrease P losses by up to 80% (McDowell, 2017). However, the LUDF farm staff currently vary irrigation depths daily according to variation in soil types and weather forecasts.

Applying too great a depth of FDE at one time can cause it to be lost in drainage (Houlbrooke et al., 2004). The use of a dedicated line suspended beneath the irrigator can result in more FDE being applied nearer the centre. A more even distribution could be gained by sluicing the FDE with irrigation water, but that would require more storage than present on the farm to remove FDE solids that cause blockages from struvite precipitation (Greaves et al., 1999). Moreover, even if the depth applied nearer the centre of the pivot was double that near the end, the depth of FDE applied at one time (on average, < 1 mm) would be well within the Code of Practice designed to minimise the leaching of FDE at 10 mm (DairyNZ, 2015). These guidelines were informed from work on poorly drained Pallic soils (Fragiochrepts in US Taxonomy; (Hewitt, 2010) where the application of FDE at a low rate (e.g. < 4 mm hr^{-1}) via small static pods over several hours did not cause the loss of FDE via preferential flow (Monaghan et al., 2008). Therefore, our data would suggest that the industry Code of Practice and good practice for the application of FDE did not prevent P leaching to depth in the free-draining and shallow Eyre soil with low ASC soil, and that this loss may not be fixed by additional investment in a low rate system. Leaching to low ASC aquifer gravels could represent a long-term source of P input to streams via baseflow (McDowell et al., 2015). Where N concentrations are low, these P inputs could induce algal blooms in summer when light and temperatures are raised and there is a long time between stormflow events (Snelder et al., 2013).

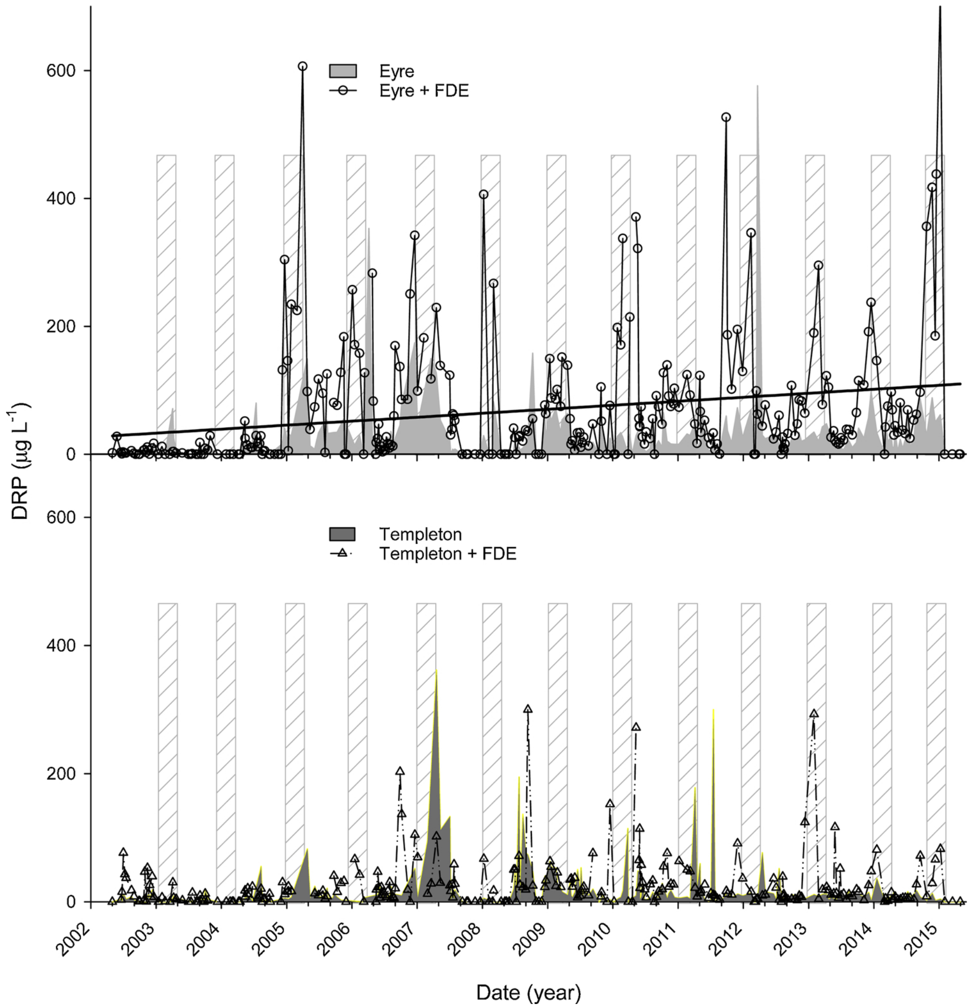

Fig. 3. Median monthly concentrations of dissolved reactive P (DRP) in drainage water over time in the Eyre and Templeton soils with or without farm dairy effluent (FDE) applied. The straight line refers to the significant fit (and 4.1% annual enrichment) of DRP over time in the Eyre soil with FDE applied using a seasonal Kendall trend test. The hatched bars refer to the months where FDE was most likely applied.

Table 4
Mean (and range in parentheses) concentrations of P fractions (μg L^{-1}) detected in seasonal samples of groundwater up-gradient, at the mid-point and down-gradient of the farm. (DRP = dissolved reactive P; DURP = dissolved unreactive P, PP = particulate P, TP = total P). The P-value is given for the contrast of mean P fraction concentrations by location.

Location	DRP	DURP	PP	TP
Up-gradient	1 (0[a]-6)	1 (0-6)	2 (0-78)	4 (2-79)
Mid-point	1 (0-22)	1 (0-8)	3 (2-72)	5 (2-74)
Down-gradient	1 (0-61)	2 (0-23)	4 (0-99)	7 (0-134)
P-value	0.466	0.778	0.108	0.441

[a] below detection limit of 1 μg L^{-1}.

4. Conclusions

Over a 14-year period the application of farm dairy FDE to a freely draining shallow Eyre soil with a low ASC gradually enriched DRP concentrations in leachate detected at 70 cm depth and in many soil layers to 60 cm depth. Across both soils and treatments, the load of TP leached from the FDE-treated Eyre soil was about six times greater than other treatments. The enhanced loss was attributed to high flow rates through macropores and to a gradual saturation of P–sorption sites within macropore walls. An enrichment of DRP concentrations over time was also measured in a well intercepting groundwater at 10 m depth down-gradient of the farm, but we cannot rule out that this enrichment may have come from other surrounding properties. These data suggest that significant P losses may occur from the shallow Eyre soil when FDE is applied despite following: 1) regulation, where FDE is not allowed to pond; 2) the industry Code of Practice to minimise leaching of FDE, and; 3) good practice where P is applied to match optimal soil Olsen P for pasture growth. While further investment could be made in applying FDE at a shallower depth and lower rate and / or less frequently, the already low rates used suggest this wouldn't decrease P losses. Therefore, less P must be applied, made less available for loss, or P-rich FDE not applied to these freely draining, shallow and stony Eyre soils under irrigation.

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